A LABORATORY-UNIVERSITY-INDUSTRY COLLABORATION FOR THE DEVELOPMENT OF MAGNETS WITH FIELDS > 22 TESLA USING HTS CONDUCTOR

A proposal to the Office of High Energy Physics, Department of Energy
(Attention Dr B P Strauss)
At a cost of $6 million for 3 years
On behalf of the
Very High Field Superconducting Magnet Collaboration (VHFSMC)

Principal Investigators
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Representing a collaboration of groups at BNL, FNAL, FSU-NHMFL, LANL, LBNL, NIST, and Texas A&M University

I. EXECUTIVE SUMMARY

The High Energy Physics Community (HEP) has identified important new physics opportunities enabled by extremely high field magnets that are beyond the ~20 Tesla (T) reach of present Nb-Ti and Nb_3Sn technology:

- 20+ T dipoles and quadrupoles for high energy hadron colliders (impact: discovery reach far beyond the present)
- 20 to 50 T solenoids for muon cooling in a neutrino factory or a muon collider (impact: understanding of neutrinos or providing a lepton collider to complement the LHC)

In addition, other communities too, as thoroughly analyzed by the National Research Council panel COHMAG (Committee on High Magnetic Fields), need a new superconducting technology. A goal of 30 T NMR magnets was set in that panel's report.

The Very High Field Superconducting Magnet Collaboration (VHFSMC) responds to this challenge. VHFSMC is targeted at developing the technology of high temperature superconductors (HTS) to take superconducting magnets well beyond the capabilities of Nb conductors. The collaboration is founded by groups from BNL, FNAL, FSU-NHMFL, LANL, LBNL, NIST, and TAMU that have been individually active in this endeavor for some years. *For reasons described in the body of the proposal, we believe that collective action is now the best way to advance this new technology for very high field superconducting magnets.*

Our effort is organized using the model of the Muon Collider collaboration. We have set in place an external oversight committee, a technical committee, a project manager and an executive committee. This proposal has been generated by the Technical Committee in a series of meetings that first convened at the 20th Magnet Technology Conference in Philadelphia in August 2007. It has a well developed first year plan organized around 6 Tasks at a cost of $2 million per year. As we are expecting rapid progress, out-year priorities will be re-evaluated annually by the technical committee within this $2M envelope, so their budgets are not broken down here. We submit the proposal as a 3 year effort with a major review in year 2 near the 18 month mark, so that optimum program redirection is assessed early.

The large accelerators at BNL, Fermilab, DESY and CERN LHC only exist because HEP was at the forefront of engineering superconductors into practical wires. These developments also enabled other vital applications, foremost among them being Magnetic Resonance Imaging (MRI). But the Nb-based materials, Nb-Ti and Nb_3Sn, upon which all this technology depends, cannot provide fields greater than 18 T in dipole magnets and 20-22 T in solenoids. In 2003, the National High Magnet Field Laboratory (NHMFL) in collaboration with Oxford Superconducting Technologies (OST) achieved a record field of 25 T in a solenoid insert made of the cuprate high temperature superconductor (HTS) $Bi_2Ca_2CuSr_2O_{8+x}$ (Bi-2212). Bi-2212 has since become available in round wires in sufficient lengths for the fabrication of small coils with Rutherford-type cables. A second proof of principle of HTS wire technology was provided in 2007 by the successful test at the NHMFL of a solenoid insert made by SuperPower from $YBa_2Cu_3O_{7-x}$ (YBCO) coated conductor. The coil achieved a new world record of 26.8 T for a superconducting magnet, making it clear that there are now at least two paths to magnets with capabilities well beyond Nb. Unlike Nb_3Sn whose irreversibility field H_{irr} is about 28 T at 1.8K, it is now clear that YBCO and Bi-2212 have $H_{irr}(4K) > 100$ T, allowing them to be used for these new applications far from their superconducting limits.

Our first choice is $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) because it can be made in the round wire conductor form (RW2212) that allows manufacture of the high current Rutherford cables, from which virtually all accelerator magnets have been made. By contrast, YBCO is a single-filament tape that is not easy to cable into multi-kiloamp conductor form. Many challenges stand between long-lengths of RW2212 that are more or less available today and their ability to enable a new high-field superconducting magnet technology. Usefully high critical current densities J_c have been measured out to the highest DC fields available (45 T), yet J_c is easily degraded by imperfect reaction and by stresses much smaller than those predicted for the coils that we want to build. The thermal-mechanical process that develops high J_c requires high temperatures with tight temperature and time constraints and a complex process that is simply not yet understood. Leakage of the $Bi_2Sr_2CaCu_2O_x$ core through the surrounding Ag metal sheath often occurs. Cabling such conductors introduces damage that compromises J_c. Protecting HTS magnets is more difficult than protecting low-temperature superconductor (LTS) magnets because of their much slower normal zone propagation. Such magnets may also need to be thermally and radiation resistant for high particle flux environments. As a result, while kilometer-long conductors are available, no real RW2212 magnets have been made, making it clear that the magnet technology is not yet established.

This collaboration directly attacks the question: **Is a round wire Bi-2212 magnet technology feasible?** Our 6 Tasks are all designed to explore practical means to make the answer – "yes"!

Our collaboration is multi-disciplinary, multi-institutional, and multi-sector, and is organized around 6 Tasks:

Task 1. Obtaining the needed high J_c and J_e in long-length RW2212 for technologically useful magnets by systematically addressing the issues of connectivity, phase development, detrimental reactions, and optimizing the heat treatment.

Task 2. Understanding the mechanical response of RW2212 conductors to axial and transverse strains.

Task 3. Fabricating RW2212 cables into the Rutherford cable forms essential for accelerator magnets.

Task 4. Understanding the quench process in RW2212 conductors and test coils so as to provide reliable protection strategies for large magnets.

Task 5. Construction of small prototype coils that provide the essential demonstration that RW2212 is ready for real magnet construction.

Task 6. Development of an integrated industrial partnership with the large and small businesses needed to make RW2212 magnets feasible.

The technical team has formulated this proposal during many meetings over the last 12 months. Progress on the Tasks will be continuously assessed by monthly video meetings and two to three face-to-face meetings per year and by a review and management structure modeled on that supporting the multi-lab Muon Collider Task Force (MUTAC). We expect the Tasks to evolve considerably, even during the first year as the collaboration develops and the magnet possibilities enabled by the effort take shape.

We make it clear that VHFSMC's goal is to develop the technology of very high field superconducting magnets. Should we conclude that Bi-2212 does not lead to a viable high field magnet technology, we will switch our focus to YBCO coated conductor or to any other emerging high-field superconductor material. But our first focus is on RW2212 because many of the crucial elements of this vital new high field technology are at hand – what the VHFSMC collaboration provides is the means to tackle the key problems interactively so as to make this new very high field magnet technology occur synergistically in a rapid and effective time frame.

II. BACKGROUND: CONDUCTORS BEYOND Nb-Ti AND Nb_3Sn:

Virtually all superconducting magnets [1] are made from Nb-Ti and Nb_3Sn. The upper limits to performance for *any* superconductor are defined by the current density J_c and the irreversibility fields H_{irr} (the field at which J_c goes to zero). At 4.2K these fields are ~10.5T for Nb-Ti and 26T for Nb_3Sn. The huge advances of $J_c(12T)$ in Nb_3Sn of the last 5 years [2] have also brought an increase in H_{irr} for Nb_3Sn from about 23T to about 26T as the Sn composition gradient in filaments has been flattened, even as the upper critical field H_{c2} has remained unchanged[3].

By contrast the high temperature superconducting cuprates have H_{irr} very far below H_{c2} over virtually their whole field-temperature *H-T* phase diagram [4]. Only at 4K where thermal fluctuations are small are H_{irr} and H_{c2} expected to be close, but good experimental data on how close is lacking. Figures 1 and 2 summarize the key data relevant to our experimental goals. H_{irr} for RW2212 is in the easily measurable low-field territory until about 20K, below which it takes off and becomes

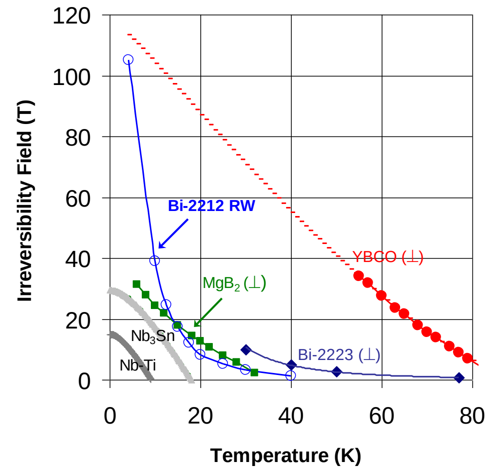


Figure 1. Irreversibility fields for representative wires of MgB_2, Bi-2212, Nb-Ti, Nb_3Sn and YBCO tape for H parallel to the axis. Data on OST RW2212 (J. Jiang unpublished) and SuperPower YBCO tape (Z. Chen unpublished) is on recent wires whose J_c is given in Fig. 2. Bi-2212 and YBCO have H_{irr} exceeding 100T, more than 3 times Nb_3Sn.

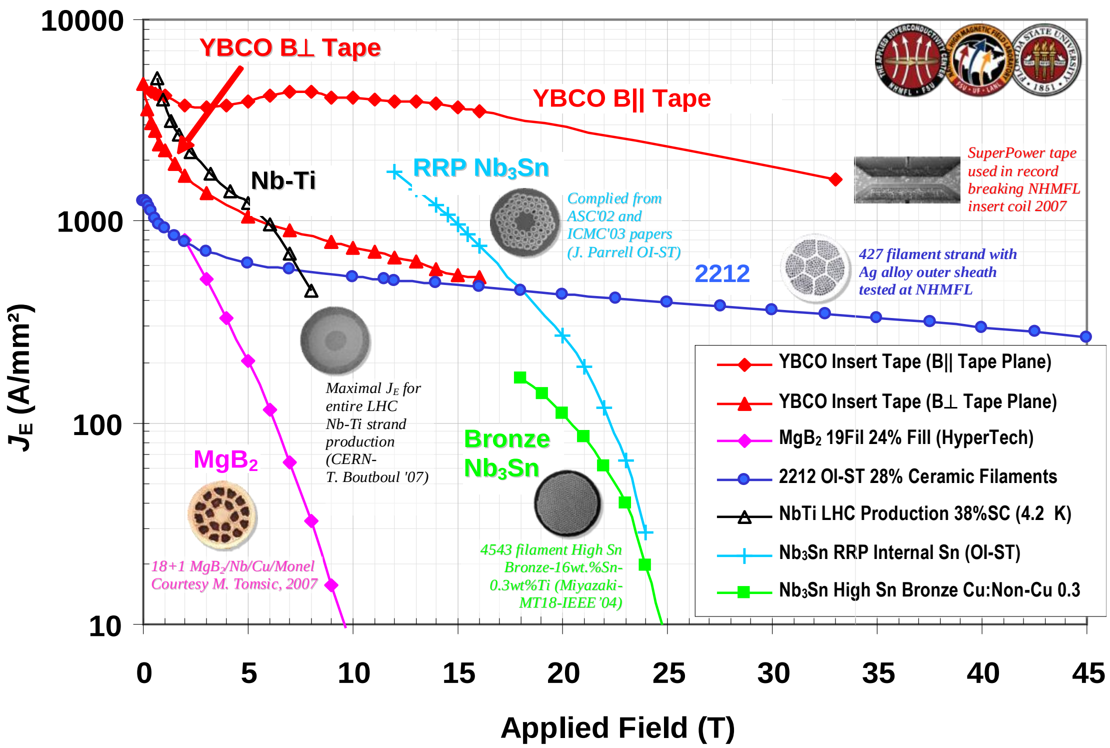


Figure 2. Engineering critical current density J_E at 4.2K for representative high J_c superconducting conductors of YBCO, MgB_2, Bi-2212, Nb-Ti and Nb_3Sn. Courtesy Peter Lee with data sourced as indicated.

very high. At present we judge H_{irr}(4K) to be ~105 T based on constancy of pinning force curve shape over the range 15-30K[5]. Given that Nb-Ti and Nb_3Sn are used up to ~80% of their H_{irr}, there is clearly enormous headroom for very high field magnets made from RW2212. Measurements on YBCO in pulsed fields suggest that $H_{c2}^{\perp ab}(0)$ is ~120 T and $H_{c2}^{||ab}(0)$ ~ 240T in the zero temperature limit.[6] Figure 2 shows that RW2212 and YBCO have engineering J_c values that exceed Nb_3Sn in the desired field range at J_E values as high as those which are used for construction of state of the art Nb_3Sn magnets today. Nevertheless it is believed that ultimate J_c values in these HTS conductors are far above those presently attained, leaving great scope for lowering the cost-performance ratio of these emerging new conductors.

The multifilament, round-wire conductor that makes a Rutherford cable technology possible has been developed over the past several years by Oxford Superconducting Technology (OST) in

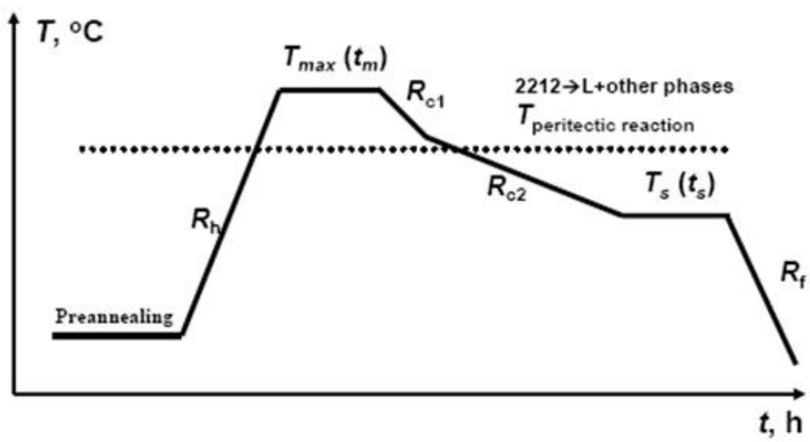


Figure 3. A typical heat treatment profile for Bi-2212 wire reaction. This empirical reaction procedure typically has tight tolerances ±2°C on T_{max}, different specifications on the heating and cooling rates R_x and secondary hold temperature and oxygen partial pressures. There is a huge need to understand what occurs during each step of the process so as to better optimize it. Quenching samples from multiple points in the process and correlating microstructure and superconducting properties is one important tool to be applied to this goal.

the US[7,8], Nexans in Europe[9,10], and Showa[11] in Japan. All have made several-hundred-meter to kilometer lengths of wire, and either alone or in collaboration, they have shown that Rutherford cabling is possible[12,13]. However, progress to an effective coil technology has been much slower than anticipated because of a number of complications that accompany the use of this conductor in a magnet form[8,14,15,16]. In no particular order we can enumerate several problems that hold back the technology at the present time:

- The reaction to develop high J_c in the wire is complex and precise, as is shown in Figure 3. During reaction, leakage of the Bi-2212 core often occurs in a few, at present apparently random, places[17]. While leakage does not appear to catastrophically destroy J_c, it is clearly an issue that needs to be understood and prevented.
- High J_c can be developed in RW2212 only because oxygen can pass freely through the metal matrix surrounding the $Bi_2Sr_2CaCu_2O_x$ filaments. The way that high J_c is developed has largely been empirical up to now. During the development of high J_c, significant growth of 2212 bridges between filaments occurs, as shown in Fig. 4[17]. Recent work[17] provides specific information about how these bridges enhance J_c and

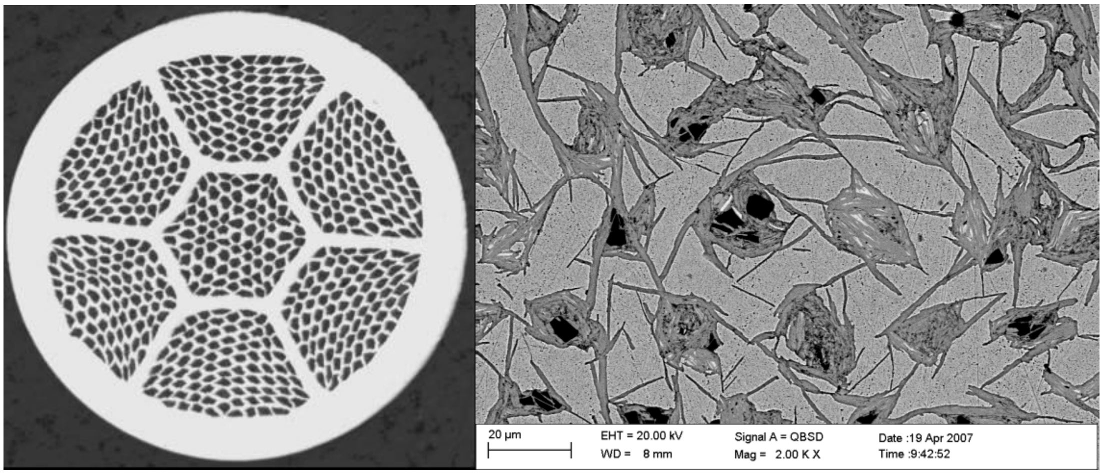


Figure 4. Cross sections of OST Bi-2212 round wire conductor before heat treatment (left image) where filaments of small-diameter BSCCO powder are well separated and after the reaction (right image) where there are many inter-filament bridges of Bi-2212 grains[17].

suggests several new experiments in collaboration with industrial producers for optimizing J_c further towards our J_E goal of 750 A/mm^2 at 20T (Table I).

- There is only one metal that is practical for the matrix that surrounds the BSCCO filaments[18],[19]: Ag. Since an essential heat treatment step takes place (~890°C) close to the melting point of Ag (962°C), pure Ag is in the dead soft condition after reaction, giving it insufficient strength to support significant magnetic stresses. Some strength is imparted to the conductor by the introduction of 0.2-0.5at.% of elements such as Mg or Al which can be internally oxidized to precipitation harden the Ag[18,19]. But for various reasons, especially reactions between the additions and the BSCCO core, this solution is not yet optimized. Thus the limits to mechanical performance of present conductors need explicit definition and enhancing.
- Cabling of conductor in the unreacted state (see Fig. 5) has been demonstrated by multiple groups[13,20,21]. Less clear is the degree of critical current degradation of cables after reaction and their tendency to leak in damaged areas.
- Normal zone propagation velocities are cm/sec in cuprates rather than the m/sec in Nb-base conductors, leading to much more localized energy deposition, higher local temperatures, and larger local temperature gradients[22]. All of these characteristics need to be understood in order to safely protect large magnets.
- Short sample performance has seldom been a convincing predictor of coil performance for any superconductor and RW2212 is no exception. Coil experience so far shows unexpected

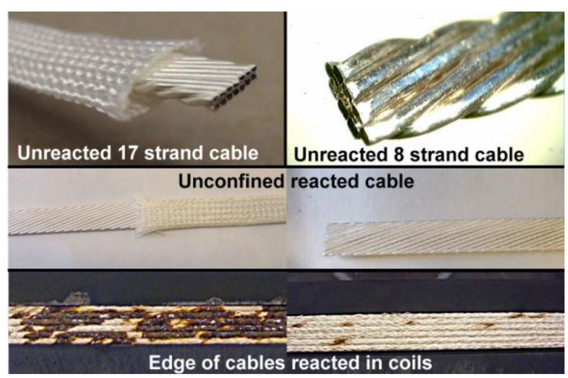


Figure 5: Full size 17-strand and sub-size 8-strand cables made at LBNL, and reacted unconfined and inside racetrack coils. Leakage is seen at lower left only for reasons that are not yet understood.

leakage and reduced J_c, as well as many reactions with common insulations and construction materials. *Small test coils are an essential part of our program to evaluate the technology.*

- The most crucial components of the technology, the raw BSCCO powder and the conductor itself, are being made industrially and supplied in quantities that are sufficient for our immediate needs. Many problems have been resolved in industry to get to this important stage and ordering additional standard conductor throughout the program will help industry in understanding the production problems. In addition it may be useful to contract for some specialized R&D services where these are complementary to the lab and university collaborators.

Early in the genesis of this proposal, a group of ~ 20 people (BNL: Arup Ghosh and Peter Wanderer; Fermilab: Emanuela Barzi, Lance Cooley, Mike Lamm, Alvin Tollestrup, and Daniel Turrioni; LANL: Ken Marken; LBNL: Dan Dietderich, Arno Godeke, Soren Prestemon and GianLuca Sabbi; FSU-NHMFL: Mark Bird, David Larbalestier, Denis Markiewicz, Justin Schwartz and Ulf Trociewitz; NIST: Najib Cheggour; Texas A&M: Peter McIntyre and Al McInturff) met by phone and in person to formulate the goals and practicality of such a proposal. We concluded that a conductor meeting many of the specifications shown in Tables I and II would get the technology off to a very strong start. In the remainder of this proposal, we present more detailed arguments as to how best to accomplish major progress towards these ambitious, but achievable, goals.

Table 1: Bi-2212 conductor development goals for magnet applications (Phase I)

Effective zero Kelvin upper critical field	≥ 40 T
20 T, 4.2 K engineering current density	≥ 750 Amm^{-2}
Filament / sub-element size	≤ 100 μm
Silver matrix resistivity at 300 K Silver matrix RRR Stable electric field along wire	<2 μΩcm ≥50 ≤ 10^{-4} V/m
Leakage during partial melt reaction	Absent
Engineering current density inhomogeneity along wire length	≤ 5%

Table 2 Bi-2212 conductor development goals for magnet applications (Phase II)

Wire twist pitch (0.8 – 1 mm diameter wire)	20 – 40 mm
Allowable wire J_E reduction due to cabling	≤ 10%
Reversible longitudinal strain regime relative to free wire cool down state	± 0.5%
Transverse Rutherford cable pressure resulting in 10% I_c reduction	≥ 100 MPa
Resistive transition index n-value at 20 T and 4.2 K	≥ 20
Piece length	≥ 2 km
Price (based on 20 T, 4.2 K performance)	<$20/kAm

In the following sections we briefly describe the thrusts of each of the sub-group efforts that are aimed at developing round-wire Bi-2212 technology for coils. We start each 2-3 page section with a brief summary of the immediate goals and then describe our program to address them. We conclude with a brief summary of the facilities at each laboratory that will enable the work.

III. TASK 1: UNDERSTAND AND DEVELOP HIGH J_C CONDUCTOR THROUGH SYSTEMATIC STUDIES OF CONNECTIVITY, PHASE DEVELOPMENT, REACTIONS, AND VARIABLE HEAT TREATMENT PARAMETERS.

Task Leader(s): Eric Hellstrom (Florida State University) and Terry Holesinger (LANL)

Budget: $650K year 1

Focus areas: Develop high J_c conductor

1. Map the optimal phase development sequence for high J_c RW2212 that occurs during the standard heat treatment. Use quench experiments to freeze-in the microstructure and electromagnetic properties of each step in today's heat treatment (HT) processes, including newer variants such as RWS (react-wind-sinter) and SPM (split melt process). **Rationale:** our current heat treatment is empirical and complex with many finicky details that are not understood, some of which are not applicable to large coils.
2. Identify the current-limiting mechanisms, especially the extents to which connectivity and vortex pinning separately control J_c in present 2212 conductor. **Rationale:** present J_c is about half of our goal. Understanding what limits J_c is essential to develop strategies to raise J_c by improved processing, alternate processing routes, new powder compositions, etc.
3. Identify the causes of leakage in present conductor, especially the degree to which extrinsic effects produced by wire or cabling (Task 3) damage play important roles. Understand the extent to which intrinsic properties of the conductor (fill factor, filament/bundle architecture, sheath material, etc.) play major roles. **Rationale:** unpredictable leakage is one of the most critical factors standing in the way of a robust RW2212 coil technology.

Implications for the Collaboration:

This Task seeks to understand whether significant improvements in coil performance can be made by solving the following conductor problems: (1) the development of microstructure and electromagnetic properties during the heat treatment is poorly understood and controlled, leaving much of the 2212 superconductor *disconnected and thus unused*; (2) the current path through the microstructure of a fiber-textured RW2212 conductor is not understood, leading to ambiguities as to what type of optimal microstructures, alternate processing routes, new powder compositions, or architectures are needed in heat treatment optimizations; (3) deviations from *precise* reaction temperature (~1% at ~880-900°C) and time lead to significant falloff of properties. Understanding would immediately improve magnet conductor J_c and coil design and construction because the present process is too complex to allow further, easy empirical optimization. (4) A significant fraction of the superconductor may *leak out of the sheath at random points along the conductor* during reaction. Understanding the sources of wire failure will lead to more reliable coil manufacturing.

Background:

Bi-2212 conductor development has been an active area of research since it was first demonstrated by Heine and co workers in 1989.[23] Subsequent work has shown dramatic improvements in wire quality and performance.[24,25] Long length wires have been incorporated into Rutherford cables for accelerator magnets in the high-energy physics community, insert coils for high-field magnets, and MRI magnet applications.[13,14,20] Ongoing issues that continue to need to be addressed are the phase development in the melt,[26 27,28,29] phase stability and compositional effects.[30,31,32,33,34,35] These issues are interconnected, making decisive experiments challenging to devise.

First-year plans:

(1) Understanding heat treatment-microstructure-property-chemistry relationships to increase J_c (FSU, LANL)

The chief obstacle to high J_c is the poor connectivity of 2212 grains, making development of proper microstructure vital. The problem is that we do not yet know what a "good" microstructure is or how it varies with starting powder composition. The highest I_c and J_c values have been obtained with superconducting compositions that are Sr-rich. Yet, looking at the microstructure (Fig. 6), it is not apparent how the current flows through the filaments. It is clear from recent studies that the 2212 bridges that grow *between* filaments during cooling step R_{c2} after melting are critical for high J_c, because they may carry as much as 2/3 of J_c [17]. Developing a specific understanding of how this (or other better) microstructure controls the important superconducting properties is our chosen route to meeting the targets of Table I while building reaction heat treatment profile flexibility for large magnets. This Task will use wire supplied by industry so that (1) multiple experiments at multiple institutions can be performed on the same batch of wire and (2) a direct line of feedback is established with the manufacturers who will ultimately be responsible for producing the needed lengths for large magnet fabrication.

To address focus area 1, we plan systematic quench experiments to freeze in the high-temperature microstructures to understand the microstructure-property-chemistry relationships. Partially reacted wires are plunged into brine, freezing in the high-temperature microstructure, which allows the microstructure and superconducting properties to be investigated at specific points during the heat treatment. These through-process studies are already showing how non-superconducting phases and pores severely limit or block current transport, how filaments bond together during cooling, and how different types of 2212 bridges grow between the filaments (Fig. 6). Because to date these studies have been done only using scanning electron microscopy, we plan to augment them with analytical (scanning) transmission electron microscopy ((S)TEM). An important unanswered question is how the 2212 connectivity occurs between grains, which can be investigated at the level of individual atomic planes by (S)TEM. (S)TEM studies are also important to understand subtle changes that occur in the 2212 during the later stages of the heat treatment.

Results from these through-process quench experiments will facilitate scientifically-based, statistical design experiments to modify the heat treatment and enhance the properties of Table I and II. Effort will be directed at studying green and reacted forms of current industry wire. This work will be based on our understanding of phase development and correlations with electromagnetic properties obtained from the quench experiments described above. Statistically-designed heat treatment studies will be undertaken to fully measure processing windows as a function of time, temperature, and oxygen partial pressure, determine process robustness, and identify areas for process improvements through reductions in thermal budgets or process variants such as RWS or SPM.

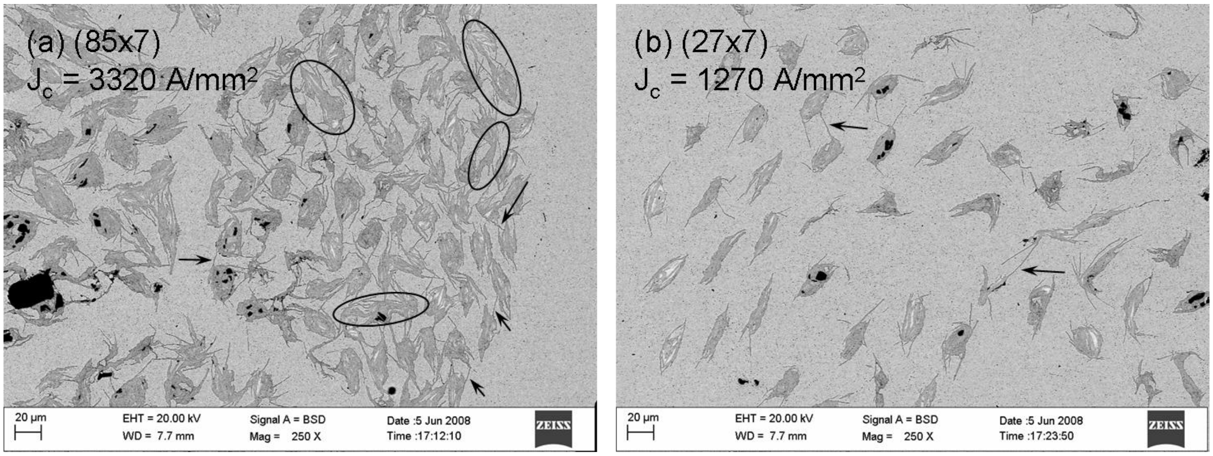


Fig. 6. SEM images of cross sections of fully-processed RW2212 wire showing 2212 bridges that grow between the filaments. (a) Standard RW2212 wire with 85 filaments in 7 bundles, designated as (85x7). J_c (4K, SF) = 3320 A/mm^2. (b) An OST R&D wire made with a (27x7) architecture by replacing ~2/3 of the 2212 filaments in a standard (85x7) wire with pure Ag filaments. J_c was only ~1/3 of the standard wire (1270 A/mm^2) for identical heat treatments. The arrows in (a) and (b) show thin bridging grains of 2212 that grew through the Ag and with one end typically terminating as a low J_c high-angle grain boundary. By contrast, the circles in (a) show thick 2212 bridges that connect neighboring filaments without significant misorientation. Quench studies at FSU are indicating that these thick, low GB misorientation angle bridges grow in step R_{c2} (Fig. 3) after filaments joined wire during cooling step R_{c1} before 2212 formation. In strong contrast to this (85x7) wire, very few of the filaments in the (27x7) wire bond during cooling because the filament spacing is much larger. The 27x7 wire thus has very few low angle 2212 bridges and J_c is strongly depressed. Remanent magnetization measurements indicate that the bridges in the (85x7) wire account for about 2/3 of the wire transport J_c.

(2) *Investigate mechanical, chemical, and strain-induced sources of composite degradation (FSU, LANL, LBNL, NIST)*

RW2212 wire is made by sheathing 2212 powder or its precursor in a Ag or Ag-alloy and partially melting the powder at ~890°C. This composite is compromised when leakage, the flow of the partial melt through the Ag during the heat treatment, decreases the amount of 2212 in the filaments and degrades the wire performance. Although easy to describe, what causes leaks has not been demonstrated yet. Recent studies point to several possibilities: leaks may form from debris or flaws in the manufacturing process; from defects created while handling the un-reacted "green" wire during braiding, cabling, or coil winding; from chemical reactions during the heat treatment that compromise the Ag sheath; from chemical reactions that pull 2212 out into the insulation; or from breakdown induced by mechanical constraint or expansion of the Ag.

During the heat treatment, the 2212 wire can be degraded by reactions with materials that are in direct contact with the wire, such as insulation, and materials that can transport to the wire as a gas phase. Reaction products may change or adhere to the Ag sheath, thereby interfering with O diffusion in and out of the sheath and the thermodynamic conditions to form the superconductor. For example, the present alumino-silicate fiber used for insulation by OI-ST (Oxford Instruments – Superconducting Technology) reacts with Ag to form a glassy phase that sticks to the Ag sheath. Such reaction products on the Ag sheath may change the mechanical response to stress and thermal expansion. The reaction between Ag and the protective oxide scale that forms on materials used for reaction mandrels, such as Inconel 600, is insidious because Cr_2O_3 etches holes in the Ag sheath as it reacts, forming $AgCrO_2$. As these examples suggest, initial focus will be on vital areas such as reactions between the wire and insulation or the coil form materials.

Out-year plans:

We expect to continue the analyses begun in year 1 in the out-years. Since we hope to obtain rapid answers to the leakage and reaction problems, emphasis will intensify on understanding microstructure formation and its relationship to J_c. We also plan to look at variations in chemistry and additives in future years to further improve J_c in wires. A limited amount of this work has already been initiated through the DOE SBIR program in a collaboration between LANL, OST, and SCI Engineered Materials. This existing work would be used to start a much broader investigation of chemistry modifications in the out years. We will also look at other possible insulation materials to see if there are adverse reactions. We need to understand why J_c in short length wire is 20-50% higher than in long length coils, what processes cause this J_c loss and means to avoid or mitigate them.

Cross-cutting opportunities:

The systematic studies of industry wires and the bases for J_c enhancements will provide excellent opportunities to integrate with Tasks 3 (Rutherford cables), 5 (coil development), and 6 (industry support). Also, the understanding of adverse insulation reactions as well as reactions with mechanical supports or coil formers will be useful to fertilize ideas in industry (Task 6) as well as cabling and small coil experiments (Tasks 3 and 5). Information about potential coatings that affect response to mechanical or thermal-expansion loads will provide opportunities for interactions between Task 2 (mechanical properties), Task 4 (quench properties), and this Task.

IV. TASK 2: MEASURE AND UNDERSTAND THE RESPONSE OF 2212 CONDUCTORS TO AXIAL AND TRANSVERSE LOADS.

Task leaders: Najib Cheggour (NIST), Arno Godeke (LBNL)

Budget: $250k year 1

Focus areas: Mechanical properties

1. Define the performance envelope of present 2212 conductors under axial and transverse loads. **Rationale:** Conductors in magnets experience large and varying loads which must be sustained reversibly (without permanent degradation) over a useful strain range. Present 2212 wires do not appear to exhibit significant reversible strain dependence and show small-strain permanent reductions of the critical current.
2. Assess the literature on strengthening materials for the matrix Ag and make preliminary assessment of reactions or other compatibility issues with BSCCO. **Rationale:** The outside region of the Ag matrix is commonly alloyed with a few tenths of a percent Mg, which can be oxidized, strengthening the Ag and resisting grain growth during the reaction. Larger amounts (a few percent) of Mg are known to increase the Ag strength by at least a factor of two, but may interfere with the 2212 reaction. A literature review of possible strengthening methods will provide guidance for longer term developments and possible implementation by manufacturers in Task 6.

Implications for the Collaboration:

This Task seeks to understand the electro-mechanical response of 2212 conductors under loads produced during manufacture, cool-down and magnet operation. 2212 is a brittle conductor, and magnetic field limits in all magnets are presently dictated mainly by the mechanical limitations of the conductor. Furthermore, in the event of a magnet quench, it is essential to protect the magnet from permanent mechanical damage arising from thermal gradients that result in large strain gradients. However, no data on recent conductors exists, making it impossible to develop design models for magnets or even to assess the feasibility of magnet structures. The provision of axial and transverse load tests will clarify the severity of the strain limitations of 2212 for high-field magnets. Integration of test data with strand design (Tasks 1 and 6) will provide a baseline for improvements that are tied directly to wire fabrication parameters.

First year plans:

(1) Axial compressive and tensile stress & strain in wires (NIST)

Early Bi-2212 tapes showed behavior that did not bode well for magnet applications. The highest critical current was obtained in the strain free state. Compressive axial strain during cool-down caused an *irreversible* reduction of the critical current of about 75% per percent of strain in these early tapes [36]. Releasing the thermal pre-compression did not restore the critical current (as in Nb_3Sn) but indicated a plateau of nearly constant I_c which extended to the irreversible strain limit. While the critical current on this plateau did not, to first order, degrade further upon cycling within the established strain history, application of additional strain outside the plateau region led to further degradation due to crack formation, and even complete loss of I_c. In short, the dominant role of cracking in determining J_c raised fears that there was no reversible regime of J_c change, which is so essential to reliable and reproducible Nb_3Sn magnet operation.

Some Bi-2212 round wires from about 5 years ago showed an irreversible strain limit as high as 0.5%, representing about a factor of 3 improvement with respect to early Bi-2212 tapes made in the 1990s [37,38], and suggest a possible small reversible strain effect [39]. These promising results will have to be re-investigated on modern 2212 wires, to find if reversibility is improved and crack formation is reduced to provide a baseline and guidance for 2212 microstructural and matrix optimizations in Task 6 of this proposal. We will therefore measure the response of the critical current in the modern 2212 wires as a function of axial tensile and compressive strain to investigate the present performance and to track improvements that will be made in the wires in this proposal. We will also measure the stress-strain characteristics of various wire layouts, as they emerge from this program, to analyze present performance and to track improvements in matrix reinforcement. Instruments to perform this Task are readily available at NIST, at LBNL, and at FSU, but in the first year the main axial strain analysis will be performed at NIST. Feedback will be given to wire manufacturers, and is targeted to lead to improved electro-mechanical performance of the strands (Task 6).

(2) Transverse pressure cable tests (LBNL)

Transverse compressive stresses have been reported to severely degrade the transport properties of unsupported 2212 wires with ~30% reduction in I_c at 100 MPa[40]. A transverse pressure test on a Rutherford cable has indicated an onset of irreversible damage occurring ~60 MPa pressure [41]. It remains crucial to understand to what extent transverse pressure induces damage and reduces the critical current in cables, since transverse loads up to ~ 200 MPa dominate high field accelerator-type magnets. Cable tests on Rutherford cables will therefore be performed using the existing infrastructure at the NHMFL split pair magnet facility, employing LBNL sample holders that have been successfully used in Nb_3Sn and earlier 2212 transverse pressure investigations. LBNL is, in the frame of the US-LARP and LBNL base programs, developing improved equipment to study the transverse pressure sensitivity of Nb_3Sn Rutherford cables. This will be made available when commissioned for 2212 Rutherford cables made from the new 2212 wires, especially to explore whether new wire designs can improve the transverse pressure tolerance of 2212 Rutherford cables.

Out-year plans:

The axial strain and stress-strain characterizations will continue at NIST and may be extended to LBNL and FSU. LBNL will start to test the stress-strain on cable stacks at 77 K to provide effective Young's moduli, needed for magnet modeling. LBNL will also start axial strain investigations on wire and explore more simplified structures such as thin films, in combination with microstructural and magneto-optical analysis at FSU, to investigate the origins of the irreversible strain dependence in 2212 in comparison to YBCO which, if well aligned, has shown to exhibit the reversible strain dependence, so desired for magnet applications[42]. FSU has planned to start to investigate fatigue in 2212 wires.

Cross-cutting opportunities:

High yield strength of the sheath will be crucial for limiting strain in the conductor due to magnet stresses. This Task will therefore fertilize Tasks 1 and 6 to monitor and improve the yield strength of Bi-2212 wires. Improvement by a factor of 2 over the present yield strength of ~100 MPa would have significant impact on the viability of high field magnets. The constraints on silver strengthening imposed by chemical reactions (Task 1) or wire formability (Task 6) will be integrated with feedback from mechanical property testing in this Task.

TASK 3: DEVELOPMENT OF 2212 CABLE TECHNOLOGY

Emanuela Barzi (FNAL), Al McInturff (TAMU & LBNL)

Budget: $250K year 1

Focus area: Cabling

1. Produce cables, characterize and establish propensity, if any, for cables to leak more than strand, and assess whether cabling produces any more damage than is seen in Nb_3Sn cables. **Rationale:** Rutherford cables are highly desirable for high field magnets with RW2212 technology – we need to start our studies with cables to understand any major issues as early as we can.
2. An alternative heat treatment approach which is more compatible with the large volumes of coils will be investigated right from the onset as a parallel effort. **Rationale:** Due to the difficulties and tight tolerances of the present heat treatment schedule, we need to explore means that build more flexibility into coil reaction..

Implications for the collaboration:

Cables reduce magnet inductance and pave the way to magnet scale-up. The main goal of this Task is to develop the best conductor technology to achieve high J_e in Bi2212 cables for high field magnets. The most immediate concern regarding cables is conductor degradation due to cabling and the amplification of cabling-induced defects by the heat treatment process. Thus, the proposed year 1 activities focus upon these issues, including cable design, development, winding and heat treatment. Progress and feedback for these goals will be determined by strand and cable characterization, as well as by joint efforts with all of the other tasks. Another important goal of this Task is to provide a standard, well characterized cable for the work in Tasks 1, 2, 4 and 5.

Year one plans:

Study of cabling and evaluation of damage (FNAL, LBNL, TAMU)

To provide reliable cables for coil construction it is necessary to minimize degradation due to the cabling process. Previous work using OST strand with different oxygen annealing processes showed that for some strand designs the I_c degradation of strands extracted from Rutherford-type cables and reacted in oxygen can be reasonable. In prior work[21], degradation was less than 20% at least up to 85% packing factor for strands which ranged in size from 0.7 to 1.02 mm, had fill factors from 22 to 28%, and J_c(12 T) between 900 and 1100 A/mm^2.

In year one we will fabricate a couple of low compaction rectangular cable designs (number of strands larger than 10 and smaller than 20) at FNAL and at LBNL for standard heat treatment and evaluation. In this Task, evaluation will be performed through electrical tests at FNAL, and SEM and MOI at FSU in Task 1. One of these cables will be used as a deliverable to the cross-cutting Tasks. As more wires become available, the most appropriate for cabling will be used to deepen the cable studies. This will include determining whether varying strand size, packing factor, relative compaction of the strand diameter at the cable edges, and/or including a core in the cable improves Rutherford-type cable performance. These studies will lead to the choice of the best performing (standard) cables for the cross-cutting Tasks.

Study and develop alternate approaches to mitigate strand damage and powder leakage (FSU, FNAL)

It is well known that Bi2212 leakage through the Ag-alloy sheath and reaction with the insulation can reduce coil performance. For instance cables tested at self-field and 4.2 K using a superconducting transformer, showed an I_c degradation of about 50%, which is significantly and systematically larger than that of the extracted strands[21]. To address these problems an alternative approach to manufacturing Bi2212 HEP magnets, “react-wind-sinter” (RWS), was developed at FSU. The RWS heat treatment increases the J_c of Bi2212 conductors by ~30-40% and, with the proper selection of heat treatment parameters, the mechanical state of RWS conductors matches that of wind-and-react conductors [43,44,45,46,47]. Here we will determine if the RWS approach is beneficial to cables, first in terms of $J_c(B,\varepsilon)$, but also to determine if the RWS approach can reduce or alleviate cabling-induced degradation. In year 1, the key questions to be addressed include: *is leakage reduced in cables given RWS processing? Does RWS reduce the severity of the temperature-time constraints of the heat treatment?* These investigations will apply lessons learned in Task 1 to development of cables for magnets, but will also complement them by factoring in the mechanical effects of winding between heat treatment steps.

In year 1, using a standard cable design developed in the first part of this Task, we will evaluate several combinations of RWS heat treatment parameters by means of electrical tests at

FNAL and FSU in this Task, and SEM and magneto optical imaging (MOI) at FSU in Task 1. Electrical tests will include I_c tests of witness round strands, I_c tests of witness extracted strands and I_c tests of unbent and bent cables.

Out year plans:

Monitor inter-strand contact resistance of cables (FNAL)

If the contact resistance between the silver-coated wires is too low, methods will have to be found to increase it, for instance by including a core in the cable or by using O_2 porous strand coating. Study of multilayer round cables (FNAL, LBNL, TAMU) may also be undertaken, particularly with respect to cabling degradation and the effect of strand mixing.

Test cables at field (LBNL, FSU, BNL)

A selected number of cables will be tested using bifilar cable samples in a cable test facility.

Cross-cutting opportunities:

This Task is cross-cutting with all other tasks in this proposal. Input from Task 1 results will lead to improved heat treatments of cables with the additional Task 3 effort of cross-linking the Task 1 input on improved heat treatment understanding with any influence on bending (which emulates winding) so as to evaluate the mechanical state of the cable after full processing. Cables manufactured in this Task will be provided to Tasks 2, 4 and 5 in support of their experiments. Results from cable characterization will provide input to Industry on the strand design.

VI. TASK 4: UNDERSTANDING THE STABILITY AND QUENCH BEHAVIOR OF CONDUCTORS AND COILS.

Task Leaders: Justin Schwartz (Florida State) and Soren Prestomon (LBNL)

Budget: $250k year 1

Focus area: Quench

1. Abundant evidence shows that quench velocities are low in present self field or low field tests, but there is some opinion that proximity to the irreversibility field will enhance velocities, thus making a test in high fields between 4 and 20 K useful. **Rationale:** HTS coils will quench and are inherently less safe in so doing – we need to define the broad nature of the issue as early as possible.
2. LTS magnets are protected through an I^2t limit that defines the protection system performance requirements. In addition to the much slower quench propagation velocity of HTS materials, there is evidence that HTS conductors may require alternative limits to prevent degradation during quenching. **Rationale**: The design of a magnet protection scheme requires an understanding of the parameter space that leads to conductor degradation. The poor mechanical properties of RW2212 and the presence of extensive defects in the microstructure warrant a thorough understanding of RW2212 quench-degradation limits.

Implications for the collaboration:

This Task seeks to understand the stability and quench behavior of RW2212 conductors and coils in high magnetic fields such that effective quench protection strategies can be developed. Understanding stability and quench behavior takes on increased importance with the development of RW2212 strand and cable for high field collider applications. Qualitatively, the underlying physics that drives quenching in LTS and HTS magnets are similar. There are significant differences in the specific quantitative details, however, that pose both opportunity and risk and must be understood to determine the technical viability of RW2212. One potential advantage of RW2212 magnets is the ability to withstand a large heat load, which makes them increasingly attractive in the particle interaction regions where increased irradiation intensity and heat load is unavoidable with increasing collider performance[48,49,50,51,52]. Self-field studies of RW2212 strand, however, indicate that the quench propagation velocity is very slow, posing significant quench detection and protection challenges. Furthermore, quench protection depends upon understanding the conductor operational limits during a quench event, and this remains unknown for RW2212 conductors.

Year-one plans:

(1) Stability and quench behavior experiments (FSU, BNL)

Self-field measurements on RW2212 strand and a single-layer coil in self-field indicate large stability margin and very slow quench propagation velocity in these conductors. The presence of a high magnetic field, however, reduces T_c and thus may significantly increase the propagation velocity. Yet high field also reduces J_c, which can lead to even slower propagation. A recent study on a RW2212 coil confirmed slow propagation in an 8.5 T background field at 4 K, but this was in a relatively low-performance coil with heaters attached only on the outer, well-cooled surface[53].

Protocols for self-field measurements have been established for short-samples and small solenoid coils that will be extended during year 1 to measurements in high magnetic fields using an 8.5 T, 200 mm superconducting magnet for day-to-day measurements and up to 20 T in the DC User Facility at the NHMFL. Measurement protocols on cables will be developed that are consistent with the short-sample and solenoid measurements and will be used in magnetic fields up to 7.5 T at the Cable Test Facility at BNL. Heaters will be mounted on heavily instrumented samples equipped with voltage and temperature measurements as a function of time and location. For three-dimensional measurements, selection of heater and instrumentation wire materials is challenging due to the requisite heat treatment. Initial studies will use surface-oxidized Inconel strip heaters and gold instrumentation wiring for twisted voltage pairs. These experiments will map the stability and quench behavior, including minimum quench energy (MQE) or temperature margin, effective current sharing temperature, and the three-dimensional quench propagation velocity, all as a function of I/I_c and background magnetic field.

Year 1 will include testing at least four single-layer, strand-wound coils at 8.5 T and two at 20 T, two multi-layer strand-wound coils at 8.5 T and one at 20 T, and six cable tests at 7.5 T. The primary goals will be to establish testing procedures for cables, determine the effect of high magnetic field on the quench propagation velocity and energy, and determine the importance of multi-dimensional quench propagation in cables and strand-wound magnets.

(2) Operational failure limits (FSU)

To design a quench protection system it is essential to know the safe conductor operating limits so as to avoid permanent magnet damage. In LTS magnets this is a maximum hot-spot temperature, often applied as an "I^2t" limit and a voltage limit. Preliminary results on RW2212 indicate that the hot-spot temperature may not provide a sufficient description and that further characterization is necessary[24,54]. Furthermore, in YBCO[55], it has been shown that non-degrading quenching, *i.e.*, quenches that do not reduce the conductor I_c, can reduce the mechanical strain limits of the conductor. Thus, not all quench damage is detected through I_c measurements, and the effects of a quench may be a reduced strain or fatigue limit. The broader implication is that, because the current carrying element in HTS conductors is a brittle ceramic, conductor damage is not always seen immediately in I_c measurements and a thorough understanding of the failure mechanisms is essential. This is more likely to be the case in Bi2212 due to its greater strain sensitivity and microstructural inhomogeneity compared to YBCO[56].

During year 1, strand failure limits will be evaluated by relaxing the sample protection limits during quench studies such that degradation thresholds for safe operation are captured. The heater pulse characteristics (amplitude, geometry and duration) will be varied such that the shape of the normal zone and relationship between end-to-end voltage and peak temperature are varied. Through this approach, the key metrics that drive degradation, e.g., maximum hot-spot temperature, thermal shock or thermal gradients, will be quantified and compared to subsequent electrical performance of the conductor. Lastly, non-degraded sections of test samples that are proximate to a degraded section will be provided to Task 2 for I_c-ε measurements to determine if the strand strain-resistance is reduced prior to I_c degradation. The primary outcome of year one will be to identify the dominant metric that leads to strand and cable failure.

(3) Modeling of quench processes (LBNL)

Experimentally-verified computer models are needed to predict the quench dynamics, determine detection limits, and estimate design criteria that minimize the risk of conductor degradation and can be implemented within a magnet-design framework. In year 1, models of wire and filament mechanics, already under development for Nb_3Sn, will be applied to RW2212. At the strand level, minimum quench energy (MQE) and 1D quench propagation need to be modeled. Quantifying MQE is critical in the design of active quench heaters, but requires detailed experiments on the field-temperature phase boundary for RW2212. The primary outcome of year one will be the development of models that can reliably predict the minimum quench energy for RW2212 wires and determine the voltage and temperature evolution of a normal zone for a multi-turn magnet. The models will be compared to quench initiation and propagation measurements on test coils. Furthermore, first models analyzing thermal-gradient-induced strain will be developed and compared to I_c-ε measurements on conductor sections subjected to strong thermal gradients; the long-term strategy being to develop models that can predict conditions leading to quench-induced conductor degradation.

Out-year plans:

We expect to continue the investigations begun in year 1 in the out-years. As the quality of strand improves through the efforts of Tasks 1, 2 (e.g., higher strength sheaths), and 6, we will evaluate their impact on stability and quench behavior, and in particular on the relationship between strand electrical performance, mechanical performance, and quench-related failure limits. Failure limits on cables will be measured and compared to the limits of individual strands.

Quench modeling will be expanded to include propagation models that predict normal zone growth and voltage rise with time, which determine quench detection time delays. The associated temperature dynamics will then feed back into the thermal/mechanical model estimating conductor degradation. Based on the refined models at the strand level, magnet-level codes/rules will be developed that allow the design of heaters and detection circuitry for HTS magnets operating in high field and at low temperature with minimal risk of damage to the magnet. Furthermore, if the experimental results and the quench modeling indicate that slow quench propagation results in a significant quench-detection-challenge, new approaches to quench detection, such as fiber-optic sensors, will be developed.

Cross-cutting opportunities

Stability and quench protection are essential elements of magnet design and operation and thus this topic is on the critical path to magnet implementation. This is evidenced by the cross-cutting opportunities of this Task. The strand-wound coils will be heat treated based upon results of Task 1 while the cables tested will be obtained from Task 3. After testing, samples will be extracted from quenched cables and coils and provided to Task 2 for evaluation. Results from Task 2 will be essential for understanding the quench-induced failure limits measured in this Task. Lastly, the key experimental and computational results from this Task will be provided to Task 5 for implementation in larger RW2212 coils.

VII. TASK 5: TEST OF PROGRAM-DEVELOPED 2212 CONDUCTORS IN A WIND-AND-REACT COIL ENVIRONMENT

Task leaders: Ulf Peter Trociewitz (FSU) and Arno Godeke (LBNL)

Budget: $100k year 1

Focus: Coils

1. Fabricate small test coils with sufficient performance, utilizing results from this proposal, to demonstrate that Wind-and-React 2212 magnet technology is a viable magnet option. **Rationale:** As a result of the complexity of the reaction and the limited strain tolerance of existing 2212 conductors, there are multiple concerns about present coil construction efforts with respect of the uniformity of oxygen partial pressure and temperature during the coil reaction cycle, the safe stress and safe quench performance limits, and appropriateness of insulation and construction materials[57,58,59]. Making many small coils as early as possible will define essential elements of the problems that our technology faces, and test progress that is made in the other tasks of this proposal in coils.
2. Understand insulation and structural material reactions in present coils. **Rationale:** At present many unpredictable and sometimes unwelcome reactions occur, rendering coil development uncertain.

Implications for the collaboration:

In this Task representative coils for solenoid and accelerator-type magnets will be developed to demonstrate the feasibility of the 2212 wires developed within this program. The coils are sufficiently large to be representative of full size coils for each application, but small enough to remain cost effective. They are the deliverable demonstrating the success of the 2212 wire development in the other tasks of present proposal in realistic, cost effective, magnet environments.

Year one plans:

(1) Accelerator-type racetracks (LBNL)

LBNL has developed a 30 cm subscale magnet series as a vehicle for coil technology development [60], with a rapid turnaround of 5 to 10 coils per year. Subscale coils are used to explore a multitude of magnet technology issues, and the most promising concepts are incorporated onto the primary development path. The success of the Nb_3Sn sub-scale program and the availability of coil fabrication tooling and four different sub-scale mechanical support structures make this approach natural for development of Bi-2212 coil technology too. It is presently being used in LBNL's base program as a test-bed for Bi-2212 coil development[12,16]. The Wind-and-React 2212 subscale coil development was initially hindered by severe leakage problems, but recent results suggest a reduction of the leakage and the possibility to reach the short sample critical current in 2212 coils[8]. The LBNL base program 2212 effort continues throughout year 1 and maintains, without charge to the present proposal, the required infra-structure needed for the out-years.

(2) High Field Solenoids (FSU)

A multi-coil high-field insert magnet is being developed at FSU-NHMFL as a stepping stone towards 30 T magnet technology. Using 2212 wire in a react and wind approach it is covering new technological ground in many ways [61,62,63,64,65]. In its current configuration, the magnet will deliver 7 T in a 30 mm bore in an existing 200 mm bore background magnet of 18 T, 4.2 K. To evaluate 2212 wire performance and provide design parameterization for the coil construction in the out-years, FSU will develop in year one a cost/performance balanced series of test coils and spirals for conductor and process evaluation, investigate the radial dependence of conductor performance in thick coils, evaluate candidate structural materials, and make a Lorentz-force tolerance test of non-externally reinforced (but impregnated) large diameter test coil in a 20 T background field. Based on the results, FSU will develop a design for a high-field insert solenoid. It is assumed that NSF core funding for the FSU-NHMFL will bear the major part of the coil construction, making conductor supply at no cost (from Task 6) essential for carrying out the proposed coil Tasks.

Out-year plans:

(1) Accelerator-type racetracks (LBNL)

A balanced cost/performance demonstrator coil target for accelerator-type magnets is a 3 T insert subscale coil in a 7 T background magnetic field that is generated with existing Nb_3Sn subscale magnets. In the out-years, LBNL will manufacture two 2x6 turn sub-scale coils from cables made in Task 3, as a technology test-bed for coil winding, reaction, potting and coil tests in self-field. When the Wind-and-React 2212 technology is sufficiently developed, the number of turns in the HTS coils will be expanded to 2x19 turns, and two fully instrumented coils will be manufactured to test for in-field field performance with quench protection. A present final target is to test a 2x19 turn racetrack coil to provide 3 T in a 7 T background magnetic field, yielding

10 T on the 2212 conductor. The required background magnetic field will be provided by existing Nb_3Sn sub-scale coils, and mechanical support structures from LBNL's base program.

(2) High Field Solenoids (FSU)

FSU will continue coil technology development targeting a 7 T or higher field insert solenoid. Engineering issues for this particular solenoid design (coil termination, joints, quench heaters) will be addressed, and quench studies addressing coil protection will be performed on sub-scale coils (collaboration with Task 4). The target insert solenoid is envisioned to be constructed from a radial stack of four coils with increasing diameter. Larger diameter sub-scale coils will be constructed and tested in-field. The insert design will be continuously refined based on emerging results and conductor development. The design will then be finalized and a 7 T insert solenoid will be manufactured, fully instrumented, and tested in the NHMFL large bore 20 T resistive magnet.

Cross-cutting opportunities

Results from Tasks 1, 2, 3, 5, and 6 will be used to evaluate and adjust racetrack and solenoid designs. Coil designs from Task 5 will help steer the development directions and priorities for the other tasks. Successful in-field tests of fully instrumented subscale racetrack coils and a 7 T insert solenoid are deliverables that will prove the viability of 2212 wires, developed within the presently proposed program, for realistic Wind-and-React magnet environments.

VIII. TASK 6: INDUSTRIAL MANUFACTURE AND COLLABORATIVE R&D.

Task Leader(s): Ken Marken (LANL) and Dan Dietderich (LBNL)

Budget: $500k year 1

Focus area: Integrate industry as an effective, vital and essential partner.

1. Maintain an industrial capability to supply 3-5 km in minimum ~300 m lengths of ~ 1mm diameter wire during 2009. **Rationale**: without a common good quality wire such as OST presently provides, different institutions cannot reliably benchmark each other and define a common base from which to exploit this technology.
2. Establish the basis for a powder specification that can be supplied by at least one and preferably more than one supplier. **Rationale:** good conductor begins with "good powder." What "good powder" is lacks scientific definition at this time, making powder replication difficult to define.
3. Purchase services and products as needed from industry. **Rationale:** Industry has produced the present product on which this technology proposal is based, partly by committing their own R&D funds to its development. We need this expertise too as we start out and should purchase R&D services where it is most expeditious to do so. RD design billets of the type shown in Fig. 6b are one such product.

Implications for the collaboration:

The goal of this program is to provide a cost-effective, high performance Bi-2212 superconductor of higher performance and quality for the high field magnets required for the next generation HEP colliders. U.S. industry involvement is crucial, both for supply of conductor for magnet development, and for continued conductor process development. Although most development scale billets have been at the ~ 1 kg scale, commercial scale 2212 wire has been demonstrated in 8 kg billets (which produce ~2 km of wire at 0.8 mm),[66] using a process that can be scaled to at least 50 kg billets. Also, short samples of industrial wire have achieved unrivaled engineering current density exceeding 200 A/mm^2 at 40 T.[67] One important challenge for this program is to attain this outstanding performance in the longer lengths of wire that have already been demonstrated.

There are two major components to this Task: delivery of the best and longest wires available to the cable and coil development activities, and continued research and development of improved processing for wire. Both of these require active participation by U.S. industrial partners that have the capability for manufacturing full scale superconducting wire.

Year-one plans:

In addition to the direct DOE funding requested in this proposal, there have been a number of SBIR awards, both Phase I and Phase II, which are relevant to the goals of this program. There has also been funding from the DOE-Conductor Development Program (CDP) program in 2007 and 2008 to continue the production with some development of Bi-2212 while VHFSMC is being established. To the extent possible, we will try to amplify our efforts in concert with them. It is recognized, however, that competitive solicitations for wire are likely required for both procurement of conductor and for the industrial R&D component of this effort.

In the first year, a solicitation will be made to interested companies for a program that is comparable to HEP's existing CDP for Nb_3Sn wire. The solicitation will have two parts: the first will be for delivery of common wire for Tasks 1-5, including the significant quantities needed to make cables and coils. It is estimated that in the first year at least 3 km of wire will be required. The second part of the solicitation will be for industrial R&D to further advance the processing and performance of the 2212 wire. The solicitation will target R&D aimed at achieving the target wire specifications of Table 1 and 2. Although it is not expected that companies will deliver to the target specification at this time, it is expected that ideas for achieving them exist. Their proposals will be graded on the quality of their approach, their track record and innovation with the companies having great freedom to choose the specific focus of their R&D.

Out-year plans:

In subsequent years we will need to establish a method for selecting the most promising processes for scale-up. The criteria will need to include both performance factors (i.e. J_E greater than 750 A/mm^2 at 20T) as well as projected large scale manufacturing costs (for $J_E(20T, 4.2K)$ = 750 A/mm^2 at a cost of \$20/kA-m or less). Although the focus in the first few years will be on understanding how properties are developed, we will not forget that the development of a cost-effective conductor and manufacturing process for full-scale magnet strands and cables is the ultimate goal of this effort.

In summary, the long term strategy of the program will be to understand and make major improvements in the key properties, while at the same time expanding the industrial production component of the program to include scale-up and cost-reduction projects as the increased funding becomes available to attack these problems. Throughout this program, we will strive to promote sharing of samples and data so that the benefits of the R&D will be available to all participants.

Cross-cutting opportunities:

Wire from Task 6 will be supplied to all other tasks of the project. The industrial efforts will interact especially strongly with Task 1, the effort to understand and increase J_c. For the first year at least, the industrial partner will be the heat treatment reference institution while the other partners establish their heat treatment capabilities for wire, coils, and cables. Industrial collaboration will also be needed for Task 3 (cable studies) and Task 4 (coil studies).

IX. FACILITIES AVAILABLE FOR CARRYING OUT THE PROPOSED WORK

Brookhaven National Laboratory

BNL has facilities to test strand at 4.2 K and up to fields of 11.5 T. In addition it has a Cable Test Facility in which meter long lengths of cables and large conductors can be tested at 4.2 K in a 68 mm bore of a dipole magnet with a uniform field length of 610 mm.

Fermi National Accelerator Laboratory

Fermilab possesses many key items needed for the proposed studies, including a compact cabling machine to fabricate cables with up to 42 strands, with any pitch value (due to electronic synchronization of wheel and caterpillar) and with minimum waste, two Teslatrons producing fields up to 16 T with magnet bores up to 77 mm, and Variable Temperature Inserts (VTI) to test at temperatures from 1.8 K to 60 K, Probes to measure I_c of HTS strands and tapes as a function of field, temperature, and field orientation, Probe to measure strand transverse pressure sensitivity at field by applying pressure on whole cable, 28 kA superconducting transformer for cable tests at self-field in VTI, Large and small coil winding capabilities, SEM equipped with EDS. In progress there is a 6 in. OD tube furnace retrofitted for reaction in oxygen, which awaits safety approval, 40 kA superconducting transformer for cable tests at field in liquid He; probe to measure the I_c of HTS strands and tapes under bending; probe to measure the I_c of HTS strands, small cables and tapes under tensile/compressive strain. In addition there is an entire industrial building devoted to magnet winding, curing and reacting. Winding tables are used for up to 4 meter long accelerator magnets and helical solenoids. Presses for curing long magnets are also available.

FSU - National High Magnetic Field Laboratory

The FSU-NHMFL has all of the essential capabilities for evaluating conductors and making small coils, including local access to the key 19 T 20 cm bore resistive solenoid magnet. This facility is available too to all comers after successful evaluation of a short proposal to NHMFL for magnet time. Short sample tests can also be run in 32 mm warm bore 45 T hybrid and 35 T resistive magnets: facilities again open to all comers. Conductor evaluation facilities are largely available in the ASC at the NHMFL, where several quench furnaces are available for 2212 work, where a very extensive field emission high resolution scanning electron microscope (Zeiss 1540esB with full analytical capability and focused ion beam with gas injectors and Omniprobe TEM sample preparation tool) is dedicated to superconductor characterization. Extensive superconducting characterization can be performed in the Applied Superconductivity

Center magnet facility that contains two Quantum Design Physical Property Measurement systems (16 T and 9T, equipped with specific heat, transport and VSM capability), as well as transport I_c measurements up to 2000 A in a 15/17T system from a very clean battery source.

Coil winding capabilities for solenoids are extensive at the NHMFL and we have recently developed a pure oxygen, high stability and high uniformity reaction furnace that we believe is capable of reacting coils up to 20 cm in diameter and 45 cm high. More than one dozen small RW2212 coils have been wound and tested in the last 12 months, the most recent being in the large diameter furnace without any apparent leakage in its 109 m of wire[68].

Lawrence Berkeley National Laboratory

LBNL's Superconducting Magnet Program has the following 2212 relevant facilities available: A 6" diameter Oxygen tube furnace. A 12" diameter pure oxygen furnace for 2212 coil heat treatment is presently being purchased. A 15 T, 64 mm bore solenoid magnet with the following probes: Two Ic(B) rigs for 4.2 K Ic measurements up to 2000 A using a helical sample layout; a straight sample Ic probe on which four samples can be measured up to 500 A in one cool-down, rendering it an ideal tool for 2212 wire heat treatment optimizations; a compact variable temperature Ic(B,T,axial strain) rig for Ic measurements up to 600 A with 1% compressive and tensile strain application, allowing the characterization of wires, tapes, thin films, bulk, and single crystals, also in terms of resistivity as a function of field, strain and temperature; a flow cryostat. A 60 stand cabling machine with a powered Turks head on which 2212 Rutherford cable development was pioneered. Infrastructure and experience to manufacture 30 cm subscale and larger 2212 racetrack, cosine theta, and tilted solenoid coils. Infrastructure to prepare cable samples for Ic and Ic(transverse pressure) tests. A 14 T, 36 mm bore dipole magnet that can be commissioned for cable measurements. A 50 kA superconducting transformer system is presently under construction. Infrastructure to test subscale 2212 racetrack coils in self-field up to 3000 A. Infrastructure to test subscale 2212 racetrack coils in four different magnet configurations with existing Nb_3Sn subscale magnets available for background field generation. The Superconducting Magnet Program also has an SEM with EDS capabilities to perform both microstructural and composition characterization of 2212 strand and Rutherford cables.

Los Alamos National Laboratory

LANL has extensive capabilities for powder development, wire development, and materials characterization, and electromagnetic measurements. Three inert dry boxes (VAC), powder milling (Retsch), solution processing equipment, and variable pressure calcination furnaces are available for high-purity powder synthesis. Spin-coating capabilities are available for powder proofing. Thermal analysis (Netzsch), x-ray diffraction (Scintag), and electron microscopy (FEI) capabilities are available for in-depth powder characterization. Facilities are also available for silver alloy development. In addition, LANL has a number of 1, 3, 6, and 12 inch, three-zone, controlled atmosphere furnaces for short wire, long-length wire, and small coil processing. Characterization facilities include capabilities for measurements up to 1600 A, D.C. at 4.2 K and self-field, superconducting characterization in a 7 T Quantum Design magnetometer, and angular dependence measurements of $I_c(H,\Theta,T)$ in 1 T and 7 T magnet systems where T can be varied in liquid cryogens in these temperature ranges: 4.2 K (He), 24-27 K (Ne), and 65 K – 87 K (pumped N_2 to Ar). Additional capabilities can be obtained at the NHMFL (LANL) with I_c measurements to 20 T (DC), pulsed field measurements to 60 T, and some specialized, pulsed measurements to 100 T. Analytical equipment for wire characterization includes x-ray diffraction, scanning electron microscopy (FEI Inspect) equipped with EDS (EDAX) and EBSD (TSL), and analytical electron microscopy (FEI TF30) equipped with EDS (EDAX) and PEELS (GATAN). TEM/STEM sample preparation is supported with a wide range of conventional dimple-polishing equipment as well as a focused ion beam (FEI) equipped with an Omni probe for TEM sample preparation.

National Institute of Standards and Technology — Boulder

NIST has a range of state-of-the-art facilities for evaluating the electromechanical properties of wire and tape conductors. We recently developed a Walters Spring for measuring the critical current of superconductors as a function of strain, temperature and magnetic field at low electric-field criteria, typically 0.01 μV/cm. The spring is designed in such a manner that it remains elastic within a large window of strain, between -1 % and +1 %. For variable-temperature measurements, the apparatus is placed inside a custom-made re-entrant Dewar with adjustable helium gas-flow rate. Temperature can be varied between 2.4 K and 100 K. The first variable-temperature measurements made on a Nb_3Sn conductor using this apparatus indicate that we can reliably measure currents in excess of 600 A at temperatures above 4 K, and close to 1000 A in liquid helium. The apparatus and re-entrant Dewar are inserted inside a 16.5/18.5 Tesla solenoid superconducting magnet. We have an apparatus for measuring stress-strain characteristics of wires and tapes at room and cryogenic temperatures (76 K and 4 K). This apparatus is equipped with a Nyilas-type extensometer (double, light weight, extensometer with a total mass of 2.4 g), and is particularly suitable for delicate samples such as Bi-2212 strands. We also have a probe for measuring the effect of transverse-compressive stress in tape conductors. This apparatus can be accommodated inside an 11 Tesla split-pair superconductor magnet. In addition, we also have a 14/16 Tesla and 12 Tesla solenoid superconductor magnets, and a number of probes for critical-current measurements as a function of temperature and magnetic field with high current capabilities, on samples mounted on ITER-like holders. Facilities for ac-loss measurements are also available.

Texas A&M University

A&M's campus has facilities to do metallurgical processing of samples, i.e.: mounting, polishing and etching. There are drawing facilities as well as modest extrusion and rolling equipment as well. There are numerous optical scopes and access to electron microscopes with the capability of EDS and XRD and skilled personnel to operate them. The Physics Dept. also has a small planetary cabling Machine. It is capable of producing several meters of small experimental cables. There is available in one of the physics labs a small short sample rig capable of 1 kilo-ampere sample current and in a 5 T background field solenoid. There is also a 10T solenoid at present cryostated for NMR work, but could be converted if needed. There is also a powder classifier and separator facility available. There is also a 10ft long Oxygen tube furnace with a seven inch tube (controlled atmosphere) aperture that has been mapped with a NIST calibrated probe and is uniform within and will control to 1°C in the mid 24" of its length..

X. PROPOSED ORGANIZATION OF THE HTS COLLABORATION

ORGANIZATION

This proposal is a collaboration whose goal is to develop the necessary technology for the next generation of magnets with fields beyond 20 T using High Temperature Superconductors (HTS) operating at LHe temperatures. It is a collaborative effort among industry, the national laboratories, and university groups that uses the existing infra structure but will require supplemental funding to carry out the proposed program.

The proposed organization for carrying out this program and monitoring both the funding and the technical progress is shown in the organization diagram below and is modeled on the successful multi-laboratory LARP and MUON Collaborations. If the proposal is accepted, the details of the final organization must be agreed upon by the DOE, the Laboratory Directors and the Collaboration. The following Directors have agreed to serve on the Oversight Group.

NHMFL Ch.	Greg. Boebinger, Director National High Magnetic Field Laboratory.
BNL	Steve Vigdor, Associate Director for Nuclear and Particle Physics
Fermilab	Steve Holmes, Associate Director for Accelerators
LBNL	J. Siegrist, Director Physics Division
NIST	Mike Kelly, Division Chief, Electromagnetics Division (ex officio)

Proposed Organization Chart

The shaded area represents the collaboration and includes the universities.

Oversight Group (OG)

The Oversight group is picked at the Directorate Level from the participating laboratories and has the responsibility of monitoring the technical and fiscal progress of the collaboration. They set up the Advisory Committee for the yearly reviews and receive its report. They forward the results of that review to the DOE along with any recommendations. They choose the Project Manager.

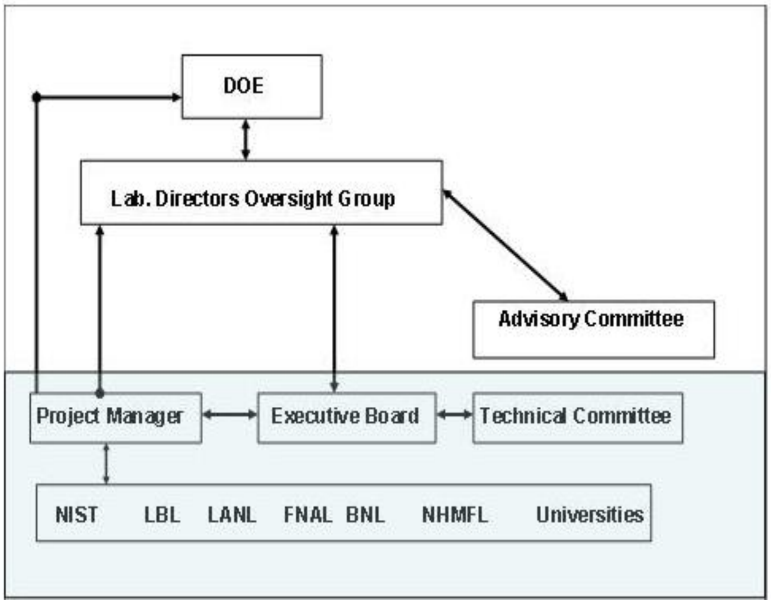
Advisory Committee (AC)

The Advisory Committee is appointed by the OG and reviews the scientific and technical progress on a yearly basis. It reports its results to the OG. It receives reports on the funding from the Project Manager as well as his report on the overall progress.

Executive Board (EB)

This Board consists of one member from each of the member laboratories. This person should be knowledgeable about the base program at his own institution and be in a position that he can commit the resources available at his institution toward support of the collaboration effort. There is also a Spokesman of the Collaboration who chairs the Board. The Spokesman is elected from the Collaboration at large by the Collaboration members. The board receives recommendations from the Technical Committee for a Project Plan and may either approve it or refer it back to the TC for modification. The function of the EB is to assure that the Collaboration has the resources to carry out the Project Plan and that it is consistent with the resources available at the individual laboratories

Technical Committee (TC)



The Technical Committee (TC) is composed of a selection of highly qualified technical experts from the collaboration. They should be familiar with the resources available in the various labs and the current critical problems that must be solved for progress. This committee does not control the base programs in the various labs, but may suggest collaborative efforts that would forward the goals of the Collaboration. The TC will have responsibility for proposing the use of funds provided by the DOE and coordinating their use with the base program. Their recommendations form a Project Plan that is submitted to the EB for approval. The Project Manager will be an ad hoc member. Individual members from the collaboration can make proposals to the TC for incorporation into the Project Plan.

Project Manager (PM)

The Project Manager receives the Project Plan from the EB and is responsible for dispersing and monitoring funds to the various individual groups doing the work. He is chosen by OG and reports to them. He also communicates with the DOE and expedites the distribution of funds. He is responsible for monitoring the progress of the Project Plan and reports the progress to both the EB and OG.

The Collaboration

The basic membership is composed from the members of the Base Program at the laboratories and universities as shown on the Organization Chart above. Membership will be open to university and laboratory members that wish to actively participate in the program. The primary requirement should be that the person or institution contributes some asset to the overall program. This could be either in the experimental or theoretical arena.

XI. REFERENCES

[1] Martin N. Wilson, *Superconducting Magnets (Monographs on Cryogenics)*, Oxford University Press, New edition (1987)

[2] See the recent compendium of papers on recent developments in Nb_3Sn, Cryogenics vol. 48 parts7/8, (2008).

[3] A. Godeke, M.C. Jewell, A.A. Squitieri, P.J. Lee, and D.C. Larbalestier, "The upper critical field of filamentary Nb_3Sn conductors", Journal of Applied Physics 97 (2005) 093909

[4] A. Geshkenbein and G. Blatter, "Vortex Matter", in the Physics of Superconductors 2003, ed by KH Bennemann and JB Ketterson (Springer, Berlin 2003).

[5] J. Jiang et al., "The Role of Filament Bridging in Bi-2212 Round Wire", presented at ASC2008, Chicago, IL, Aug. 2008.

[6] Sekitani, T., N. Miura, et al. "Upper critical field for optimally-doped $YBa_2Cu_3O_{7-x}$." Physica B-Condensed Matter 346: 319-324 (2004).

[7] K. R. Marken, H. Miao, M. Meinesz, B. Czabaj, and S. Hong, "BSCCO-2212 conductor research at Oxford Superconducting Technology," *IEEE Transactions on Applied Superconductivity*, vol. 13, pp. 3335-3338, 2003

[8] Z. Melhem et al., "Quench Behavior and Analysis of Bi-2212 Wind and React Coils," presented at ASC2008, Chicago, IL, Aug. 2008.

[9] M.O. Rikel, S. Arsac, E. Soileux, J. Ehrenberg, J. Bock, K. Marken, H. Miao, C.E. Bruzek, S. Pavard, A. Matsumoto, E.E. Hellstrom, and L. Motowidlo, Effect of composition on the melting behaviour of Bi2212-Ag conductors, Journal of Physics: Conference Series 43 (2006) 51-4

[10] M.O. Rikel, A. Wolf, S. Arsac, M. Zimmer, and J. Bock, "Effect of precursor phase composition on 2223 phase formation in Ag-sheathed tapes," IEEE Transactions on Applied Superconductivity, 15, (2005) 2499-502

[11] T. Koizumi, T. Hasegawa, J. Nishioka, Y. Hikichi, T. Nakatsu, H. Kumakura, H. Kitaguchi, A. Matsumoto, and S. Nagaya, Bi-2212 phase formation process in multifilamentary Bi-2212/Ag wires and tapes, IEEE Transactions on Applied Superconductivity 15 (2005) 2538-2541.

[12] A. Godeke, D. Cheng, D.R. Dietderich, C.D. English, H. Felice, C.R. Hannaford, S.O. Prestemon, G. Sabbi, R.M. Scanlan, Y. Hikichi, J. Nishioka, and T. Hasegawa, Development of wind-and-react Bi-2212 accelerator magnet technology, IEEE Transactions on Applied Superconductivity 18 (2008) 516-519

[13] T. Hasegawa, J. Nishioka, N. Ohtani, Y. Hikichi, R. M. Scanlan, R. Gupta, N. Hirano, and S. Nagaya, "12 kA HTS Rutherford Cable," IEEE Transactions on Applied Superconductivity, vol. 14, pp. 1066-1069, 2004

[14] H. W. Weijers, U. P. Trociewitz, K. R. Marken, M. Meinesz, H. Miao, and J. Schwartz, "The generation of 25.05 T using a 5.11 T $Bi_2Sr_2CaCu_2Ox$ superconducting insert magnet," *Superconductor Science and Technology*, vol. 17, pp. 636-644, 2004

[15] T. Koizumi, T. Nakatsu, N. Ohtani, Y. Aoki, T. Hasegawa, N. Hirano, and S. Nagaya, "Development of large current capacity Bi-2212 monolithic conductors", Physica C 392-396 (2003) 1025-9.

[16] A. Godeke, D. Cheng, D.R. Dieterich, P. Ferracin, S.O. Prestemon, G. Sabbi, R.M. Scanlan, "Limits of NbTi and Nb_3Sn, and development of W&R Bi-2212 high field accelerator magnets", IEEE Transactions on Applied Superconductivity 17 (2007) 1149-52

[17] Presentations on 2212 by T. Shen et al., by J. Jiang et al., by F. Kametani at al., by E. Hellstrom et al., by U. Trociewitz at al.; by X. Liu et al.; by D. Meyers et al.; and by M. LoSchiavo et al. at ASC2008, Chicago, IL, Aug. 2008.

[18] J. Tenbrink and H. Krauth, "Thermal expansion properties of Bi-2212 in Ag or an Ag-alloy matrix", Superconductor Science & Technology 7 (1994) 754-8

[19] M.O. Rikel and W. Goldacker, "Kinetics and mechanism of low-temperature internal oxidation of Ag-2 and 4 at.% Mg alloys", Journal of Materials Research 14 (1999) 2436-2445

[20] R. M. Scanlan, D. R. Dietderich, H. C. Higley, K. R. Marken, L. R. Motowidlo, R. Sokolowski, and T. Hasegawa, "Fabrication and test results for Rutherford-type cables made from BSCCO strands," *IEEE Transactions on Applied Superconductivity*, vol. 9, pp. 130-133, 1999.

[21] E. Barzi et al., "BSCCO-2212 Wire and Cable Studies," *Advances in Cryogenic Engineering* 53 (2008).

[22] T. Effio, U.P. Trociewitz, X. Wang and J. Schwartz, "Quench induced degradation in $Bi_2Sr_2CaCu_2O_x$ tape conductors at 4.2 K," *Superconductor Science & Technology* **21** 045010 (10pp) (2008)

[23] K. Heine, J. Tenbrink, and M. Thoner, "High-field critical current densities in $Bi_2Sr_2CaCu_2O_x$ /Ag wires," *Applied Physics Letters*, vol. 55, pp. 2441-2443, 1989.

[24] H. Miao, H. Kitaguchi, H. Kumakura, K. Togano, T. Hasegawa, and T. Koizumi, "$Bi_2Sr_2CaCu_2O_x$ / Ag multilayer tapes with J_c > 500,000 A/cm^2 at 4.2 K and 10 T by using pre-annealing and intermediate rolling process," *Physica C*, vol. 303, pp. 81-90, 1998.

[25] T. G. Holesinger, J. A. Kennison, K. R. Marken, H. Miao, M. Meinesz, and S. Campbell, "Compositional and microstructural analysis of high Ic and Jc Bi-2212 conductors`," *IEEE Transactions on Applied Superconductivity*, vol. 15, pp. 2562-2565, 2005.

[26] R. D. Ray II and E. E. Hellstrom, "Ag-clad Bi-Sr-Ca-Cu-O wires I: phase study of fully processed 2:2:1:2 wires," *Physica C*, vol. 172, pp. 435-440, 1991.

[27] R. D. Ray II and E. E. Hellstrom, "Ag-clad Bi-Sr-Ca-Cu-O wires II. Important factors in supersolidus phase studies," *Physica C*, vol. 175, pp. 255-260, 1991.

[28] W. Wong-Ng, L. P. Cook, and F. Jiang, "Melting equilibria of the Bi-Sr-Ca-Cu-O (BSCCO) system in air: the primary crystallization phase field of the 2212 phase and the effect of silver addition," *Journal of the American Ceramic Society*, vol. 81, pp. 1829-1838, 1998.

[29] J. Polonka, M. Xu, A.I. Goldman, D.K. Finnemore, and Q. Li, Melting and freezing of bismuth strontium calcium copper oxide compounds, Superconducting Science and Technology **5** (1992) 157-S160

[30] J. MacManus-Driscoll, P. C. Wang, J. C. Bravman, and R. B. Beyers, "Phase equilibria and melt processing of $Bi_2Sr_2CaCu_2O_{8+x}$ tapes at reduced oxygen partial pressures," *Applied Physics Letters*, vol. 65, pp. 2872-2875, 1994.

[31] T. G. Holesinger, "Al_2O_3 additions for isothermal melt processing of $Bi_2Sr_2CaCu_2O_x$," Journal of Materials Research, vol. 11, pp. 2135-2141, 1996.

[32] W. Zhang, E. A. Goodilin, and E. E. Hellstrom, "Composition studies for Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ conductors processed in 100% O2," Superconductor Science and Technology, vol. 9, pp. 211-217, 1996.

[33] P. Majewski, "Phase diagram studies in the system Bi-Pb-Sr-Ca-Cu-O-Ag," Superconductor Science and Technology, vol. 10, pp. 453-466, 1997.

[34] M. Okada, "Development of Bi-2212/Ag round-shaped wire and magnet application," Superconductor Science and Technology, vol. 13, pp. 29-33, 2000.

[35] D. Sager, M. Koch, B, Hallstedt, L.J. Gauckler, M. Chen, "Enhanced residual secondary phase dissolution by atmosphere control in Bi-2212 superconductors", Physica C 405 (2004) 103-116.

[36] B. ten Haken, A. Godeke, H. J. Schuver, and H. H. J. ten Kate, IEEE Trans. Magn., vol. 32, no. 4, p. 2720, 1996.

[37] J. Schwartz, H. Sekine, T. Asano, T. Kuroda, K. Inoue and H. Maeda, "Fabrication, Current Density and Strain Dependence of Sintered, Ag-Sheathed Bi-Sr-Ca-Cu-0 (2212) Single Filament and Multifilamentary Tape Superconductors," IEEE Transactions on Magnetics 27(2) (1991) 1247

[38] J. Schwartz, B.C. Amm, H. Garmestani, D.K. Hilton, and Y. Hascicek, "Mechanical Properties and Strain Effects in $Bi_2Sr_2CaCu_2O_x$ /AgMg Composite Conductors," IEEE Trans. on Applied Superconductivity 7(2) (1997) 2038.

[39] N. Cheggour, unpublished data

[40] J. W. Ekin et al., IEEE Transactions on Applied Superconductivity 11 (2001) 3389

[41] D. R. Dietderich et al., IEEE Transactions on Applied Superconductivity 11(1) (2001) 3577

[42] D.C. van der Laan and J.W. Ekin, Applied Physics Letters 90 (2007) 052506

[43] S. Boutemy, J. Kessler, and J. Schwartz, "React-Wind-and-Sinter Technique for Bi2Sr2CaCu2O8 High Tc Coils," *IEEE Transactions on Applied Superconductivity* 7(2), 1552-1555 (1997)

[44] J. Schwartz and G.A. Merritt, "Proof-of-principle experiments for react-wind-sinter manufacturing of $Bi_2Sr_2CaCu_2O_x$ magnets," *Superconductor Science and Technology Rapid Communication* 20 L59—L62 (2007)

[45] J. Schwartz, T. Effio, X. Liu, Q.V. Le, A.L. Mbaruku, H.J. Schneider-Muntau, T. Shen, H. Song, U.P. Trociewitz, X.R. Wang and H.W. Weijers, "High field superconducting solenoids via high temperature superconductors," *IEEE Transactions on Applied Superconductivity* 18(2) 70—81 (2008).

[46] T.M. Shen, X.T. Liu, U.P. Trociewitz, W.T. Nachtrab, T. Wong and J. Schwartz, "Mechanical behavior of Bi2Sr2CaCu2Ox conductor using a split melt process for react-wind-sinter magnet fabrication," *IEEE Transactions on Applied Superconductivity* 18(2) 520 (2008).

[47] X.T. Liu, T.M. Shen, U.P. Trociewitz and J. Schwartz, "React-wind-sinter processing of high superconductor fraction $Bi_2Sr_2CaCu_2O_x$/AgMg round wire," *IEEE Transactions on Applied Superconductivity* **18**(2) 1179 (2008).

[48] R. Gupta, M. Anerella, M. Harrison, J. Schmalzle, and N. Mokhov, "Open midplane dipole design for LHC IR upgrade," *IEEE Transactions on Applied Superconductivity,* vol. 14, pp. 259-262, 2004

[49] R. Gupta and M. Harrison, "Interaction region magnets for VLHC," *IEEE Transactions on Applied Superconductivity,* vol. 12, pp. 81-85, 2002

[50] A. Devred, S. A. Gourlay, and A. Yamamoto, "Future accelerator magnet needs," *IEEE Transactions on Applied Superconductivity,* vol. 15, pp. 1192-1199, 2005

[51] N. K. Mokhov, D. R. Chichili, S. A. Gourlay, S. V. Sciver, and A. Zeller, "Superconducting magnets in high-radiation environment at supercolliders," in *Super magnets for Supercolliders Workshop,* Erice, Sicily, 2003

[52] D. Bocian, B. Dehning, and A. Siemko, "Modeling of quench limit for steady state heat deposits in LHC magnets," *IEEE Transactions on Applied Superconductivity,* vol. 18, pp. 112-115, Jun 2008.

[53] U.P. Trociewitz, B. Czabaj, S. Hong, Y. Huang, D.C. Knoll, D.C. Larbalestier, W.D. Markiewicz, H. Miao, M. Meinesz, X. Wang and J. Schwartz, "Quench studies on a layer-wound $Bi_2Sr_2CaCu_2O_x$ /AgX coil at 4.2 K," *Superconductor Science & Technology* **21** 025015 (5pp) (2008)

[54] T. Effio, "Quench Induced Degradation in $Bi_2Sr_2CaCu_2O_{8+x}$ at 4.2 K," M.S. Thesis, Florida State University, 2008

[55] A. L. Mbaruku, U. P. Trociewitz, X. Wang, and J. Schwartz, "Relationships between conductor damage, quenching and electromechanical behavior in YBCO coated conductors," *IEEE Transactions on Applied Superconductivity,* vol. 17, pp. 3044-3049, Jun 2007

[56] A. L. Mbaruku and J. Schwartz, "Statistical analysis of the electromechanical behavior of AgMg sheathed $Bi_2Sr_2CaCu_2O_x$ superconducting tapes using Weibull distributions," *Journal of Applied Physics,* vol. 101, 2007

[57] S.C. Kim, D.W. Ha, S.S. Oh, I.Y. Han, C.E. Bruzek, J.G. Oh, H.S. Sohn, Study on thermo-mechanical treatment in fabrication of Bi2212/Ag HTS wire, Cryogenics 47 (2007) 437 – 441.

[58] K. R. Marken, Jr., H. Miao, M. Meinesz, B. Czabaj, S. Hong, Progress in Bi-2212 Wires for High Magnetic Field Applications, IEEE Trans. Appl. Supercond. 16/2 (2006) 992 – 995.

[59] M. O. Rikel, D. Wesolowskii, A. A. Polyanskii, X. Y. Cai, K. Marken, H. Miao, E. E. Hellstrom, Effect of solidification conditions on microstructure of melt processed Bi2212/Ag conductors, Physica C vol. 372-376, Part 3 (2002) 1839-1842.

[60] R. R. Hafalia et al., IEEE Trans. Appl. Supercond., vol. 13, no. 2, p.1258, 2003.

[61] H. Miao, K. R. Marken, M. Meinesz, B. Czabaj, S. Hong, A. Twin, P. Noonan, U. P. Trociewitz, J. Schwartz, High Field Insert Coils From Bi-2212/Ag Round Wires, IEEE Trans. Appl. Supercond. 17/2 (2007) 2262 – 2265.

[62] W. D. Markiewicz, J. R. Miller, J. Schwartz, U. P. Trociewitz, H. W. Weijers, Perspective on a Superconducting 30 T/1.3 GHz NMR Spectrometer Magnet, IEEE Trans. Appl. Supercond. 16/2 (2006) 1523 – 1526.

[63] H.W. Weijers, U. P. Trociewitz, K Marken, M. Meinesz, H. Miao, J. Schwartz, The Generation of 25.05 T using a 5.11 T $Bi_2Sr_2CaCu_2O_x$ Superconducting Insert, Magnet Supercond. Sci. Technol. 17 (2004) 636 – 644.

[64] K. Fukushima, K. Tanaka, T. Wakuda, M. Okada, K. Ohata, J. Sato, T. Kioshi, H. Wada, Fabrication and Transport Properties of Bi-2212/Ag prototype magnets for 1 GHz-NMR Magnet System, Physica C 357-360 (2001) 1297 – 1301.

[65] H.W. Weijers, Q. Y. Hu, Y. S. Hascicek, A. Godeke, A., Y. Viouchkov, E. Celik, J. Schwartz, K. Marken, W. Dai, J. Parrell, Development of 3 T class Bi-2212 insert coils for high field NMR, IEEE Trans. Appl. Supercond. 9 (1999) 563 – 566.

[66] K. Marken, private communication, SCI-OST SBIR 2005.

[67] H. Miao, K.R. Marken, M. Meinesz, B. Czabaj, and S. Hong, IEEE Trans. Appl. Supercon. Vol 15 pp 2554-2557 2005.

[68] U. Trociewitz et al., talk presented at the August 2008 Applied Superconductivity Conference in Chicago